The effect of removing B coatings from the Alcator C-Mod Tokamak

- Review previous operation with boronized walls
- B removal process
- D/H removal process
- Differences in operation pre- and post-boronization
- W tile progress
- Summary

PPPL PFC meeting

May 9-11, 2005

Presented by B. Lipschultz

Contributions from D. Whyte. J. Terry, B. LaBombard, Y. Lin and the C-Mod Team

Why is the study of operational experience with high-Z PFCs important?

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- ITER will potentially operate with all metal walls. Certainly, DEMO almost has to (radiation and T retention).
- It may not be possible to boronize/condition walls in ITER/DEMO
  - Need to know if this leads to problems for ITER
  - Need to know if there is some ‘active’ method of wall conditioning
- We need better information on where the high-Z impurity sources are and how to control them
- We need better information on the D/T retention in those surfaces AND how to remove it.

Historical perspective

- All surfaces have been boronized on a regular basis since January 1996.
  - Confinement (H factor) enhanced by roughly x 2 over unboronized walls.
  - Plasmas more steady state
  - Lowered Mo levels
  - Lowered levels of low-Z impurities
- Concerns arose
  - Confinement appeared to be degrading over years
  - Layers were accumulating (> 5 um thick)
    - Not sure of effect on operation
  - Difficult to control H/D (ICRF heating)
  - ITER-relevant to compare strictly high-Z operation to boronized surfaces

D/H retention thought to be controlled by thick B layers

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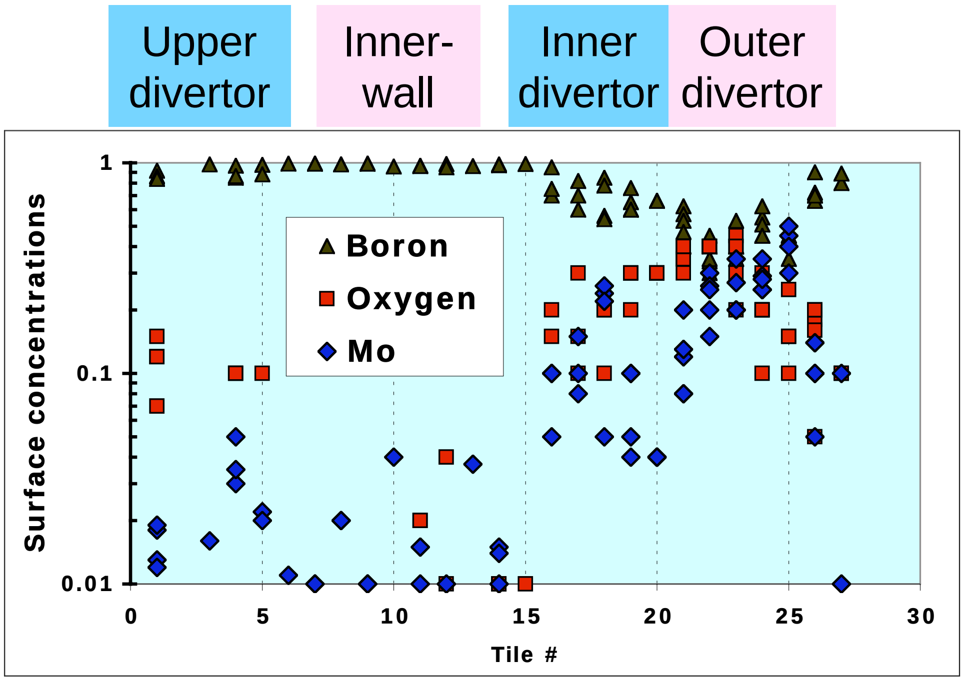
Results (Whyte tile analysis)

- Outer divertor
  - Net erosion
  - Intermixed B and Mo
- Inner divertor
  - Net B deposition (~ 1nm/s)=> co-deposition
- Generally accumulation over many boronizations
  - ~ 6 micron thicknesses
  - Burying D & H -> bad for D/H control
- Results contributed to decision to clean the machine of B
- Would like the ability to localize boronization



Significant D & B on the sides of tiles

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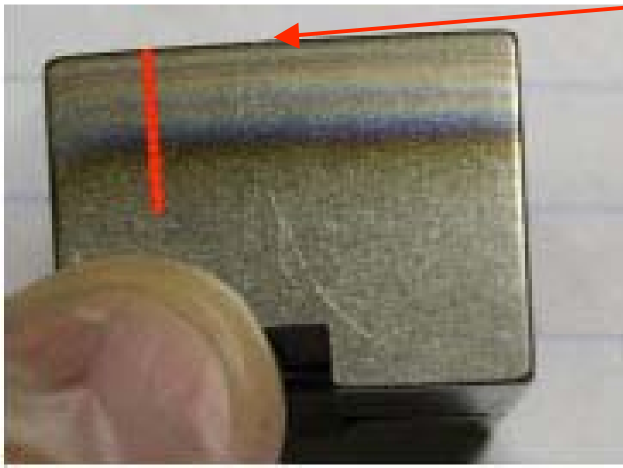
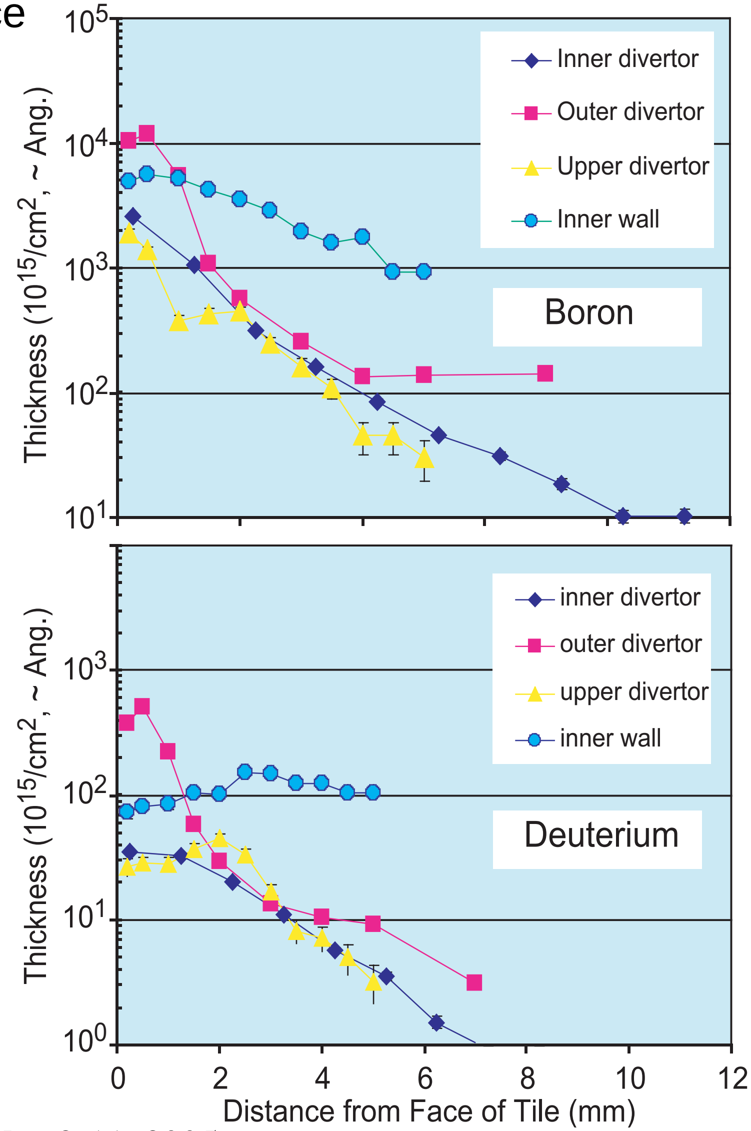


Front surface



- Ion beam analysis
  - NRA and RBS; 1 mm spotsize
- Thickness near front surface ~ 1 μm
- Thickness e-folding length ≥ spotsize
- D/B
  - ~ 0.2% near tile front
  - Increases to ~ 1% farther away
- Accounts for an additional 20% D inventory beyond front surfaces

Boronization on Alcator C-Mod

- Typically deposit 5 g of boron during a boronization
  - 10% B_2D_6 in 90% helium
  - 12 hours of electron cyclotron discharge to deposit the B
  - ~100 nm deposition
- Boronize again after approximately 200 discharges after
  - Moly radiation increases
  - H/(H+D) ratio increases and affects ICRF heating

Boron removal process

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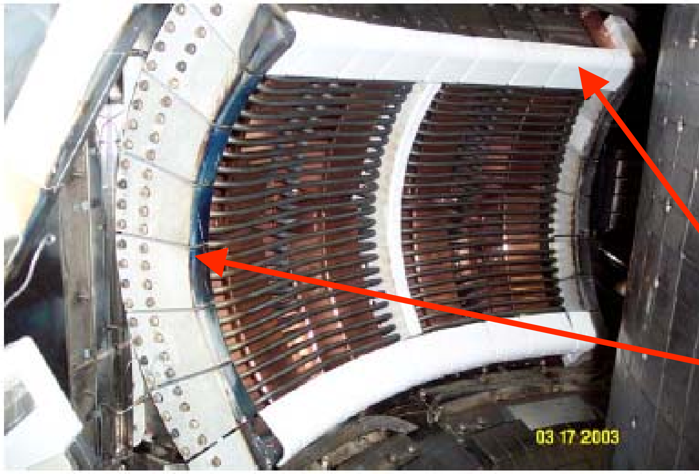
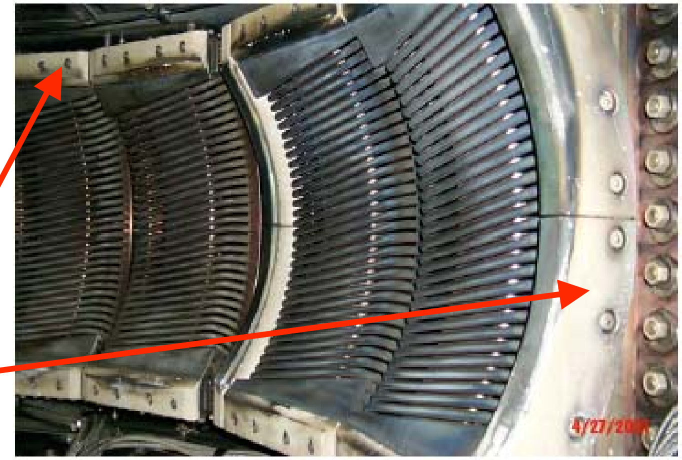
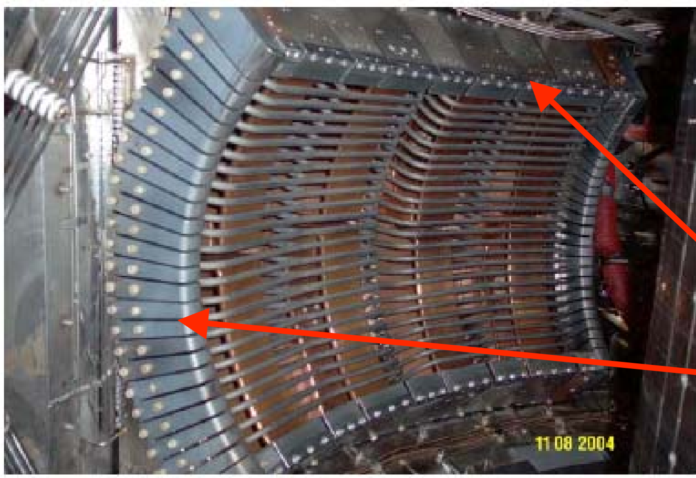
- All in-vessel surfaces and surfaces beneath the divertor modules were vacuumed.
- Mo tile modules (160 total), mostly on the inner wall and ceiling, were removed from the machine and ultrasonically cleaned.
- All inner and outer divertor tiles were wiped down in-situ.
  - Such tile modules were difficult to remove for ultrasonic cleaning.
- All other in-vessel surfaces, including outboard limiters, stainless steel vessel walls, and cable trays were wiped down.

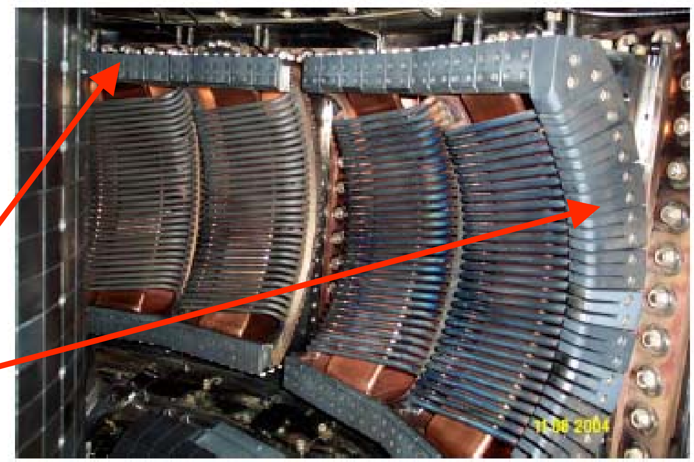
Antenna tiles also changed over to Mo





BN tiles (before)



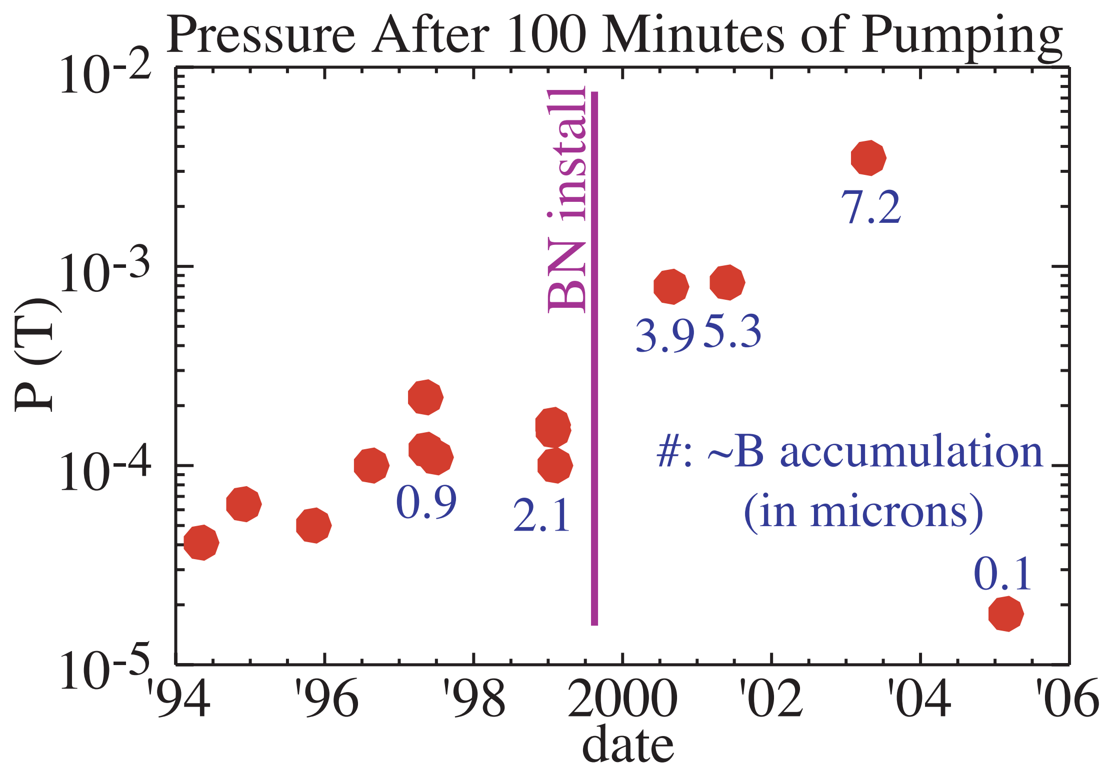


Mo tiles

J antenna

D and E antennas

Pumpdown shortened after B removal



- Accumulation of B appears to enhance adsorbed H_2O and prolong pumpdown.

H removal rate not noticeably improved

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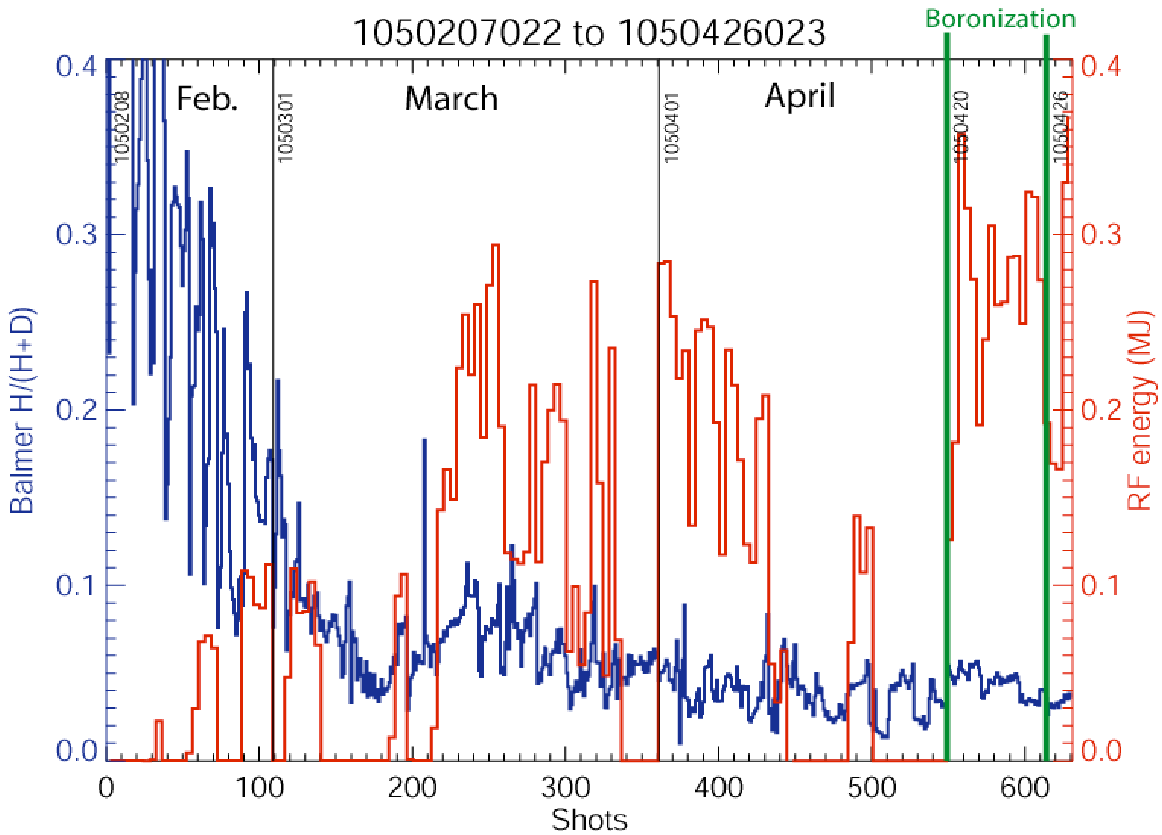

- H absorbed in tile during vent at ~ 0.4D/B
- Energy injected increases H removal rate
- RGA spectra after shot reflect this trend

- Consistent with Whyte results (5% D found in B and Mo)
  - =>similar results for boronized and Mo surfaces
  - =>want better removal of H before covering with B layer.

Intentional disruptive discharges efficient in H/D removal from Mo

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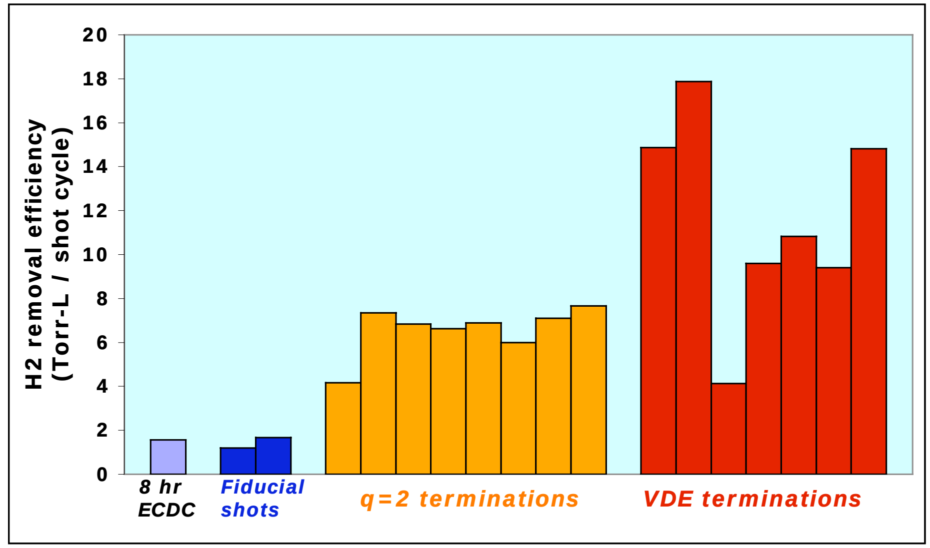
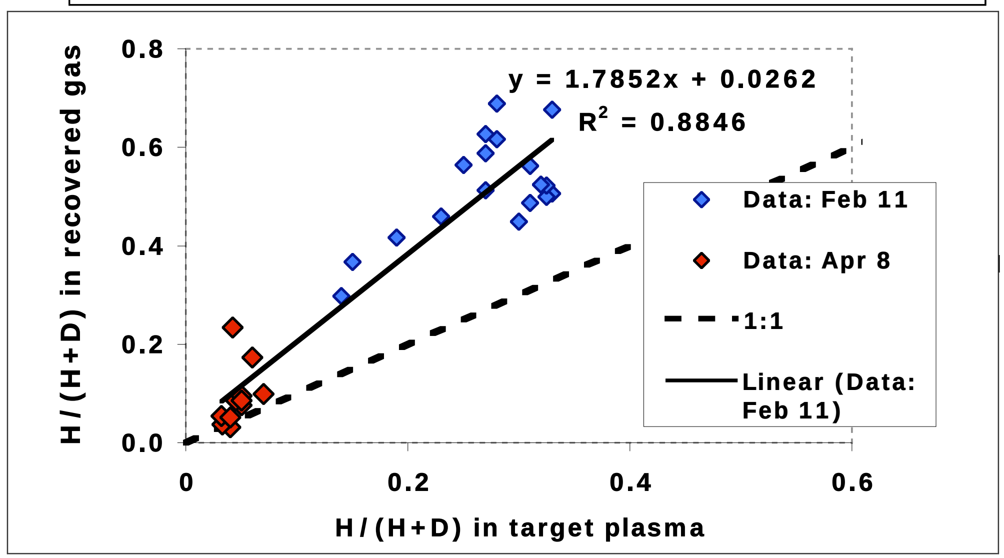
Idea - concentrate heat flux locally to raise surface temperature - outgas H/D

- Disruptions release more gas than 'regular' shots or wall conditioning
- On this day recovered
  - 250 Torr-l H2
  - 180 Torr-l D2
  - 140 Torr-l D2 injected



- H/(H+D) of plasma and recovered gas clearly correlated
  - February data right after vent - giving high H/(H+D)
  - April data just before boronization (low H/D)
  - Not 1:1 because of gas puffing during discharge
- H removed through isotope exchange (HD as opposed to H2)



Non-linear dependence of liberated gas on plasma energy

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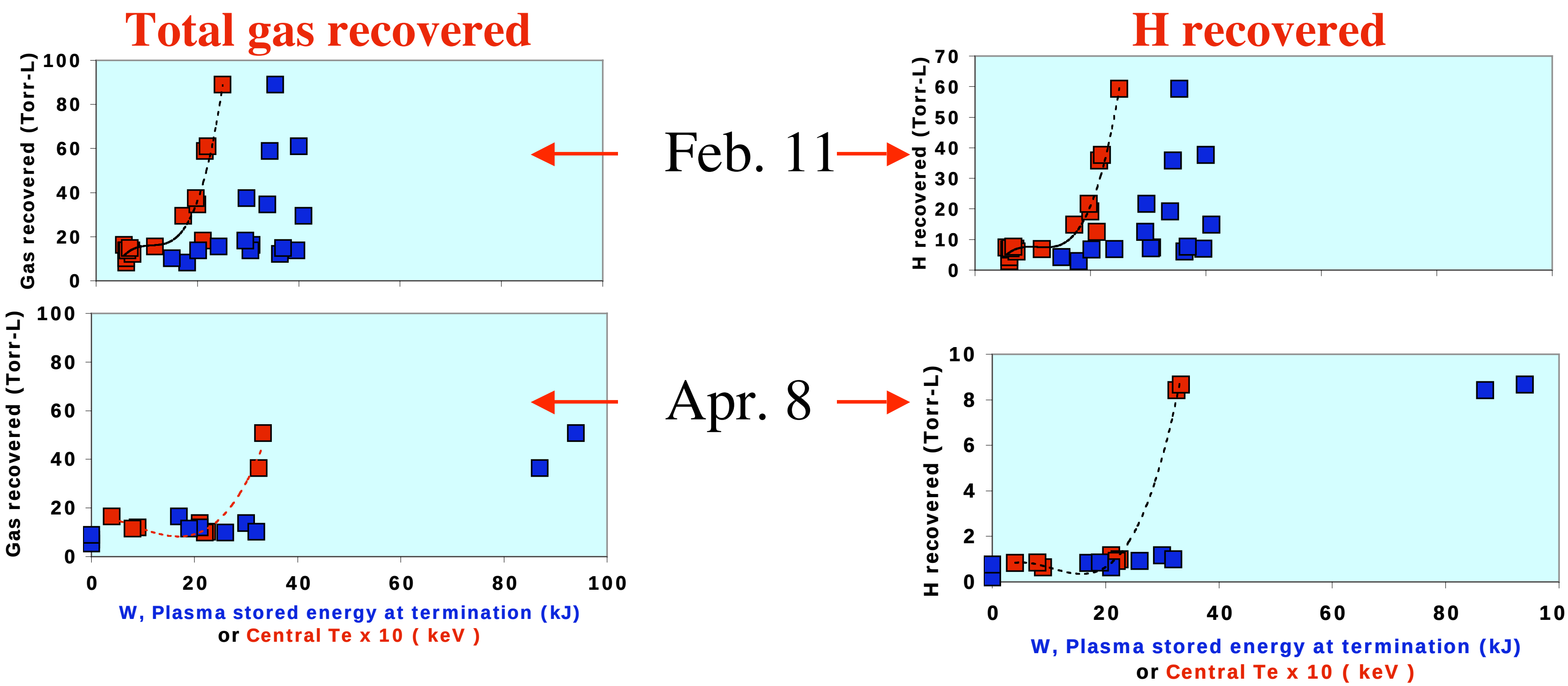

- W_{th}/T_e threshold increased over time, but later run had less evolved gas and lower H/D
- Comparison of recovered gases with repeat downward ohmic VDE with W_{th} ~ 30 kJ, T_e~ 2 keV, $D_{2,inject}$ ~ 13 Torr-L
  - Feb. 11 (#18): recovered gas = 35 Torr-L H = 19 Torr-L (H/D ~ 55%)
  - Apr. 8 (#18) : recovered gas = 10 Torr-L H = 1 Torr-L (H/D ~ 10%)

Wall pumping not affected by change in wall

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- Prior to this run period we observed ‘wall pumping’
  - ~ 5-10 Torr-l/shot
  - Blamed on co-deposition of D with B
  - Over a whole day total pumped tended to 0 (disruptions…)
- This run period, prior to boronization wall pumping still observed
  - Level comparable to last run period
  - Cannot be co-deposition
  - Further work needed to sort this out

- Bottom line: B-covered wall and Mo wall are similar from the D gas point of view.

Scaling of antenna sources and radiation (pre-boronization L-mode)

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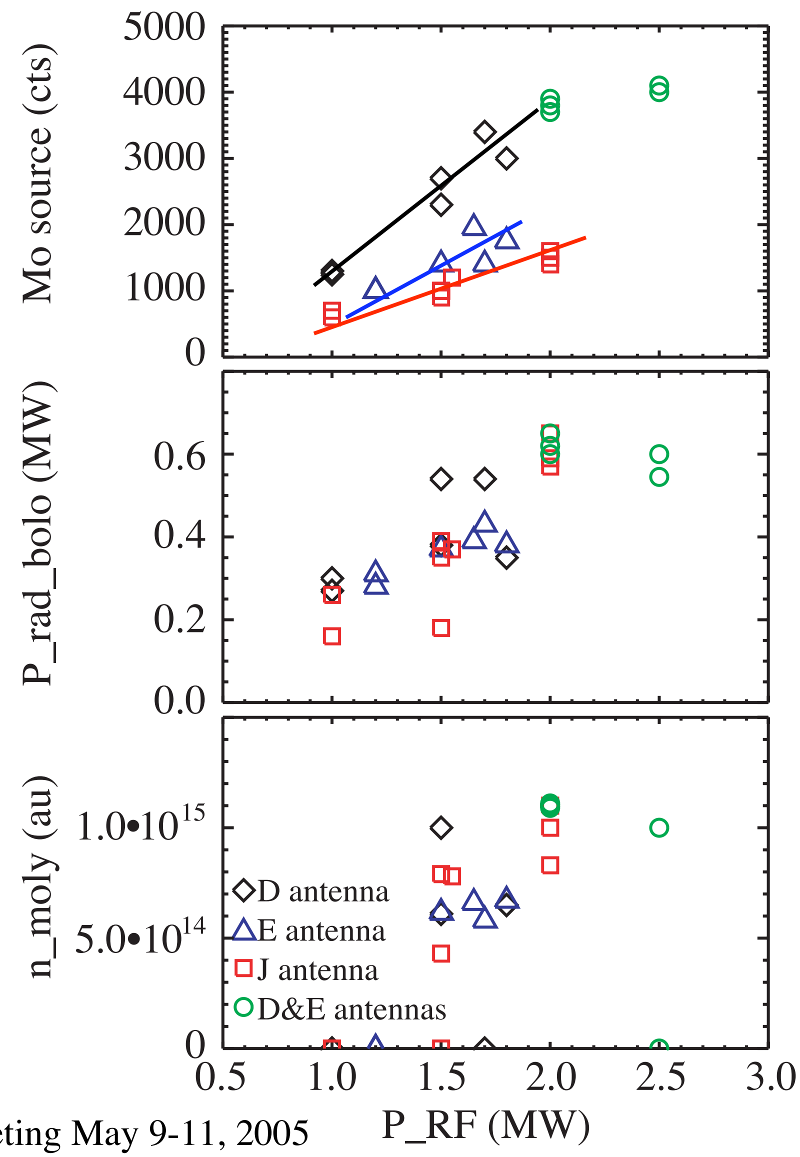
- Sources scale roughly linearly with RF power
  - Sources at a given antenna also occur when other antennas are on
- Main radiated power appears to correlate with PRF as well.
- Core Mo density generally correlates with sources and P_{RF}. Can't trust the absolute number density (calibration, interpretation issues).



Wall conditioning experiments before boronization

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- Expediting H/D change-over through planned disruptions:
  - Removed up to 80 Torr-l of (H+D)/disruption.
- Firing Li pellets into double null plasmas:
  - No obvious effects on plasma parameters.
- Injecting boron particles into plasmas:
  - ~10 mg boron injected/discharge. Raised n_B/n_e level from .03% to ~ 1%. No effect on confinement.
    - B itself does not lead to improved confinement
- Boronizing the machine:
  - Significant enhancement on plasma performance
  - Reduced the impurities level and radiated power.

Boronization lowered impurities

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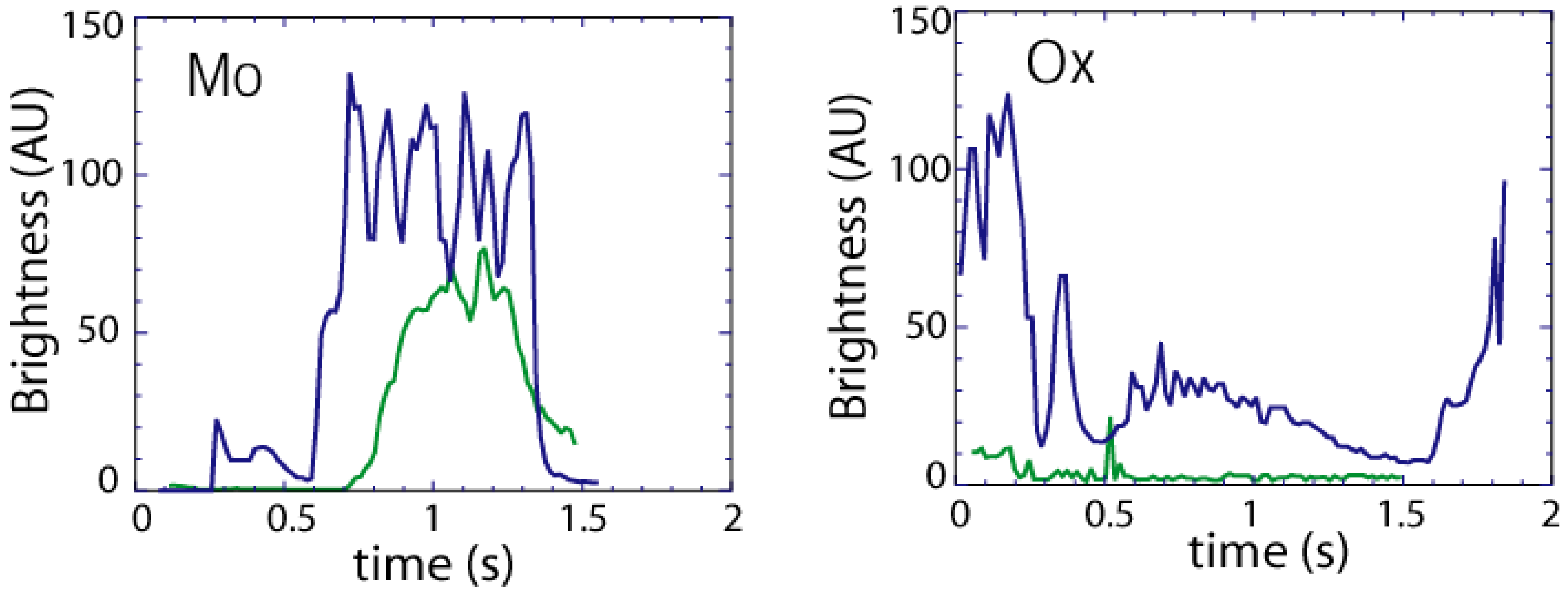

Pre-boronization shot: Prf = 3 MW, Prad = 2 MW, Wtot 120 kJ

Post 1st boronization shot: Prf = 4 MW, Prad = 1.8 MW, Wtot = 220 kJ

Post 2nd boronization: The Mo level is further down by a factor of 2-10.

- Mo is usually the dominant contributor to radiated power in the confined plasma, but we have not eliminated everything

Boronization enhanced performance

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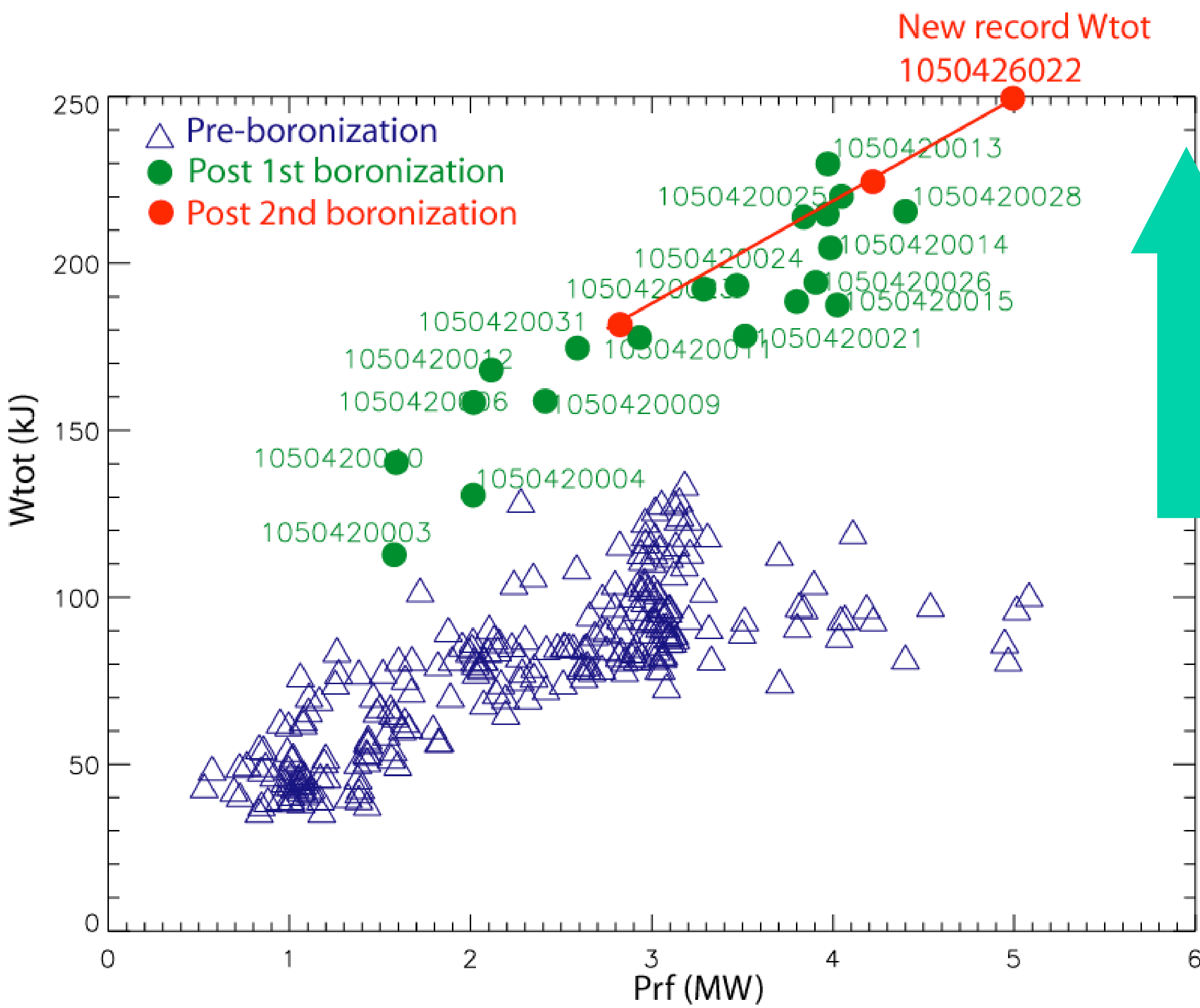
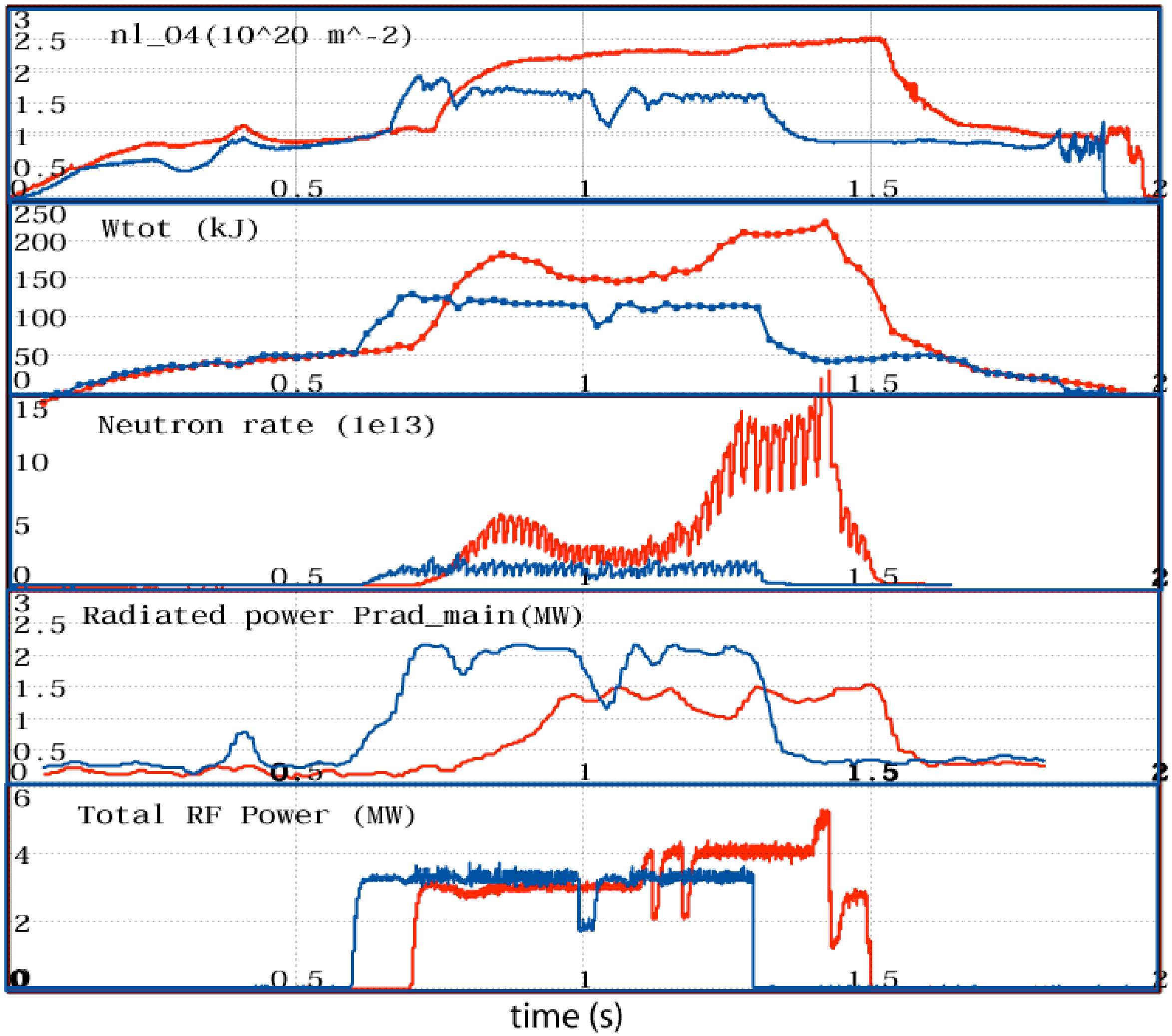


Wtot more than doubled

Boronization reduced radiation

Blue: Pre-boronization (1050401007) Red: Post-boronization (1050426016)

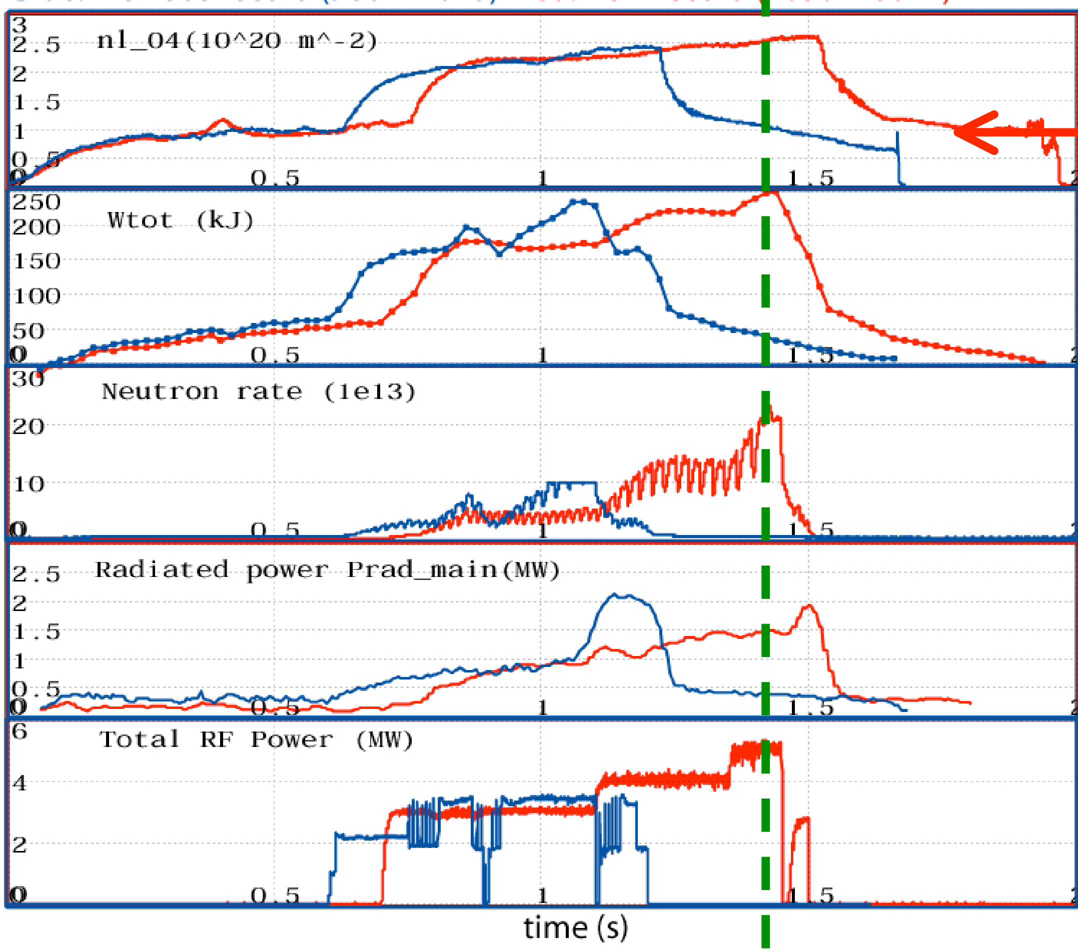


Substantially higher stored energy

Significantly lower radiation

Record plasma pressure achieved

Blue: Previous record (980217015) Red: New record (1050426022)



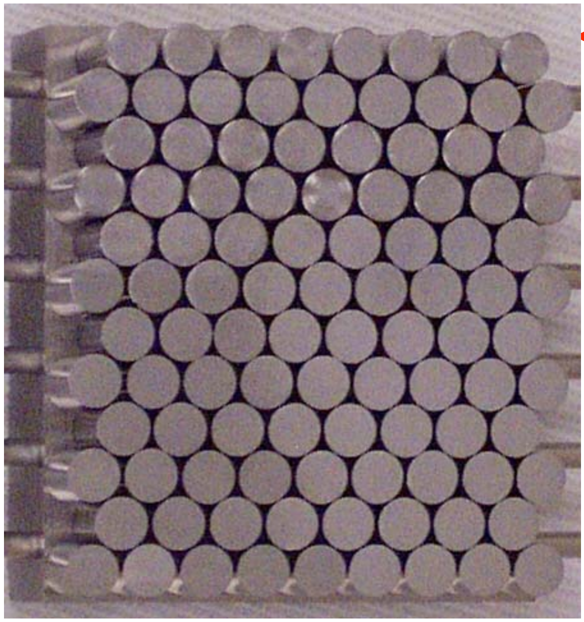
Record total average plasma pressure 1.6 atmospheres

H_{89} ~ 2

$H_{ITER98y2}$ ~ 1

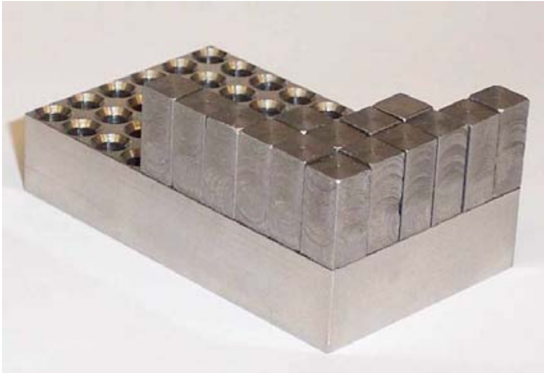
Average plasma performance on run 1050426 exceeded the best runs in C-Mod operation history.

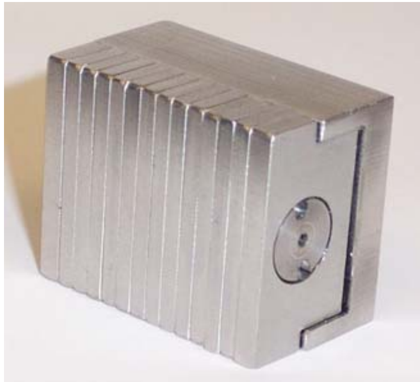
Tungsten tile status

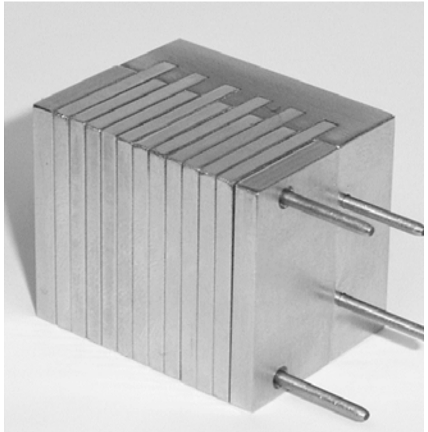


- 12 W-rod tiles installed in the divertor and being used in high heat flux regions
  - Leading edges
  - Separatrix strike point region
- New designs being worked on
  - Square rods (less leading edges)
  - Stacked W plates
    - Poorer grain properties
    - Much cheaper and higher thermal mass
    - Plans for installation of ~ 1/10 the outer divertor next up to air.

New W prototype tiles being developed







- Range of designs being pursued
- Plate design cheapest by far
  - Question of whether it will withstand heat loads
- Plans to install ~ 1/10 divertor w/W tiles next winter

C-Mod providing an important testbed for high-Z PFC studies

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- Effect of boronization
  - Adsorbed H/D better in high-Z
  - Absorbed H/D appears similar for high-Z and boronized surfaces
  - Wall pumping similar
    - => B and Mo wall similar with respect to H/D, ~ 5% D in near surface
  - Impurities down
  - Stored energy up
    - => although impurity decrease important, not sure if this is all that boronization does. Don't know if boronization required for ITER.
- Developing techniques for H/D removal (good for ITER)
- W-brush tiles installed and used in high heat flux regions
- New prototype tiles being prepared